

The dark knight falters

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ABSTRACT

Tentative line emission at 111 and 129 GeV from 16 unassociated *Fermi*-LAT point sources has been reported recently by Su & Finkbeiner (2012c). Together with similar features seen by *Fermi* in a region near the Galactic Centre, the evidence has been interpreted as the spectral signature of dark matter annihilation or internal bremsstrahlung. Through a combination of supervised machine-learning algorithms and archival multiwavelength observations we find that 14 out of the 16 unassociated sources showing the line emission in the Su & Finkbeiner sample are most likely active galactic nuclei (AGN). Based on this new evidence, one must widen the range of possible solutions for the 100–140 GeV excess to include a very distinct astrophysical explanation. While we cannot rule out a dark matter origin for the line emission in the Galactic Centre, we posit that if the detection in the Su & Finkbeiner sample is indeed real it might be related to accretion, bubble, or jet activity in nearby ($z < 0.2$) AGN. Alternatively, given the right conditions, the similarity could be due to a chance occurrence caused by extragalactic background light (EBL) absorption. Or else one must concede that the features are an artefact of instrumental or calibration issues.

Key words: (cosmology:) dark matter – gamma-rays: observations – galaxies: active

1 INTRODUCTION

Frantic activity has ensued over the past few months following the report of an excess of *Fermi* gamma-ray events clustered around 100 and 140 GeV in a region near the Galactic Centre (Weniger 2012; Su & Finkbeiner 2012b). Dark matter annihilation and internal bremsstrahlung have rapidly emerged as possible explanations (Bringmann et al. 2012; Weniger 2012). Alternative interpretations have also been advanced (Profumo & Linden 2012; Boyarsky, Malyshev & Ruchayskiy 2012; Aharonian, Khangulyan & Malyshev 2012). More recently things have heated up even further with a tantalising claim of similar line emission at 111 and 129 GeV in 16 unassociated sources detected in the Second *Fermi*-LAT catalogue (2FGL). The detection could provide independent support for a dark matter origin for the line emission seen near the Galactic Centre region (Su & Finkbeiner 2012c). Certainly, such coincidence might not only help us unlock the mysteries of dark matter, but it would also prove the existence of dark matter subhaloes (Klypin et al. 1999; Moore et al. 1999; Springel et al. 2008).

In the absence of obvious flaws in the analysis, the collected evidence has risen as a sort of dark knight – albeit an indirect one – that might finally grant us non-gravitational

access to dark matter. Intrigued by this possibility, we explore the nature of the 16 *Fermi* unassociated sources listed by Su & Finkbeiner (2012c). Based on machine-learning classification algorithms and multiwavelength examination, we show that 14 out of the 16 unassociated *Fermi* sources displaying the lines are likely gamma-ray AGN. Therefore, rather than strengthening the argument, the detection of an identical signal in the Su & Finkbeiner sample appears to disprove a dark matter origin for the *Fermi* features unless a set of very unique astrophysical conditions are met.

The paper is structured as follows. In Section 2 we explain the machine-learning classifier *Sibyl*. In Section 3 we compile class prediction for the 16 unassociated *Fermi* sources listed in Su & Finkbeiner (2012c). Section 4 details multiwavelength searches for the potential counterparts of these 16 objects. Finally, we provide some interpretation in Section 5.

2 SIBYL

Initially, we want to examine whether the set of unassociated sources showing line emission at 111 and 129 GeV (Su & Finkbeiner 2012c) is distinct in any way when compared to the bulk of associated *Fermi* sources. Confirmation of a truly unique type of gamma-ray source would hint that we may have finally found the much sought-after dark mat-

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ter subhaloes predicted by numerical simulations. As our base for such comparison, we use *Sibyl*, a Random Forests classifier that generates predictions on class memberships for unassociated *Fermi*-LAT sources using gamma-ray spectral features extracted from the 2FGL (Mirabal et al. 2012). Random Forests (RF) create an ensemble of classifiers with a tree structure, where the splits captures the complexity of the feature space among the set of training objects (Breiman 2001). To tag a new object, RF lets each classifier vote and then outputs a prediction based on the majority of votes ($P > 0.5$). RF also computes proximities between pairs of objects and quantifies which variables are instrumental to individual classification. Previously we performed a similar analysis for unassociated 2FGL sources at $|b| \geq 10^\circ$ (Mirabal et al. 2012). Here, we extend the coverage down to $|b| \geq 5^\circ$ in order to encompass the entire Su & Finkbeiner sample. The classifier presented has been implemented with the R randomForest package (Liaw & Wiener 2002).

As in Mirabal et al. (2012), we trained *Sibyl* using 800 labelled AGNs (BL Lacs and flat-spectrum radio quasars only) and 108 pulsars from the the complete *Fermi* LAT 2FGL catalogue (Abdo et al. 2010; Ackermann et al. 2011; Abdo et al. 2012). There are additional gamma-ray classes in the 2FGL, but since the 16 unassociated sources in the Su & Finkbeiner (2012c) lie at $|b| \geq 5^\circ$ we do not expect noticeable contamination from Galactic plane sources. The main task thus is to find out whether the unassociated sample from Su & Finkbeiner (2012c) falls into these two categories or it is clearly different from these types of objects.

During training and testing with the 908 labelled sources, we used a total of 7 spectral features: Index, Curve, Variability, and Flux Ratios (FR_{12} , FR_{23} , FR_{34} , and FR_{45}) (Mirabal et al. 2012). Assuming class bimodality, *Sibyl* achieves an accuracy rate of 97.1% based on majority voting (97.7% for AGNs and 96.5% for pulsars). Inspection of the results shows that misidentifications tend to occur when less than 70% of the individual classifiers ($P < 0.7$) agree on a particular prediction. Therefore we set this threshold as our internal limit for a valid prediction.

3 APPLICATION TO THE SU & FINKBEINER SAMPLE

For each of the 16 unassociated *Fermi* sources listed in Su & Finkbeiner (2012c), *Sibyl* provides a prediction that the object is an AGN (P_{AGN}) or a pulsar (P_{Pulsar}) based on individual votes tallied from the classifiers. We adopt a threshold $P > 0.7$ to accept a prediction *i.e.*, at least 70% of the trees agree on the final decision. Conservatively, sources failing to reach the threshold remain formally unassociated and most likely constitute interesting gamma-ray sources. In total, *Sibyl* predicts 14 objects in the Su & Finkbeiner sample to be AGN. The resulting predictions and percentages of voting agreements are listed in Table 1. Only two objects 2FGL J1716.6–0526c and 2FGL J1721.5–0718c remain without a firm prediction. We note that both sources are also the only ones fitted with LogParabola functions in the Su & Finkbeiner sample. But such a pair is not uncommon as there are at least 163 associated *Fermi* sources with LogParabola best fittings in the 2FGL including numerous AGN, pulsars, and supernova remnants (Abdo et al. 2012).

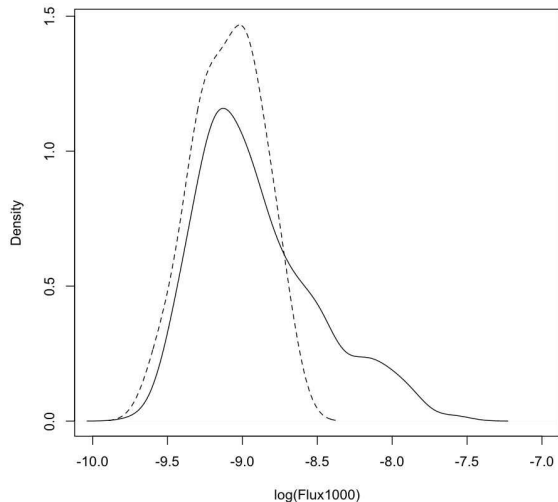


Figure 1. Kernel density plot of the 1–100 GeV photon flux Flux1000 ($\text{photons cm}^{-2} \text{s}^{-1}$) for the 573 unassociated sources listed in the 2FGL (solid). Comparison with the 16 unassociated sources in the Su & Finkbeiner sample (dashed). There is no obvious difference between the peaks of the samples.

Furthermore, none of the objects appears to be an outlier (Mirabal et al. 2012) or has been strongly suspected to be a potential dark matter subhalo candidate in any of the previous searches conducted to date (Buckley & Hooper 2010; Nieto et al. 2011; Belikov, Hooper & Buckley 2011; Zechlin et al. 2011; Ackermann et al. 2012; Mirabal et al. 2012). Lastly, the photon flux distribution for the 16 unassociated sources is compared to the overall distribution for the full *Fermi*-LAT unassociated sample (573 sources) in Figure 1. Except for a slight mismatch at the very bright end, we find no obvious selection effects that could produce line emission in this particular set.

4 MULTIWAVELENGTH EXAMINATION

To the untrained eye, it might seem overly simplistic to rely on machine-learning algorithms to make a class prediction for a particular source. We simply refer the reader to the vast amount of research and applications of classification methods that have managed to reach tremendous accuracies in a variety of astrophysical subfields (Bloom & Richards 2011; Richards et al. 2012). However, one must never forget that a smart computer generated guess is no substitute for observation¹. We take this recommendation at heart and move the association process even further by searching for the actual counterparts in archival multiwavelength observations that have partially or fully covered the *Fermi* 95% confidence error ellipses of the 16 unassociated sources. For this purpose, we employ a set of well-validated strategies (Mirabal et al. 2000; Reimer et al. 2001; Mukherjee et al. 2002).

The wide distribution of sources over the sky results

¹ Paraphrasing a philosophical note by Random Forests creator Leo Breiman

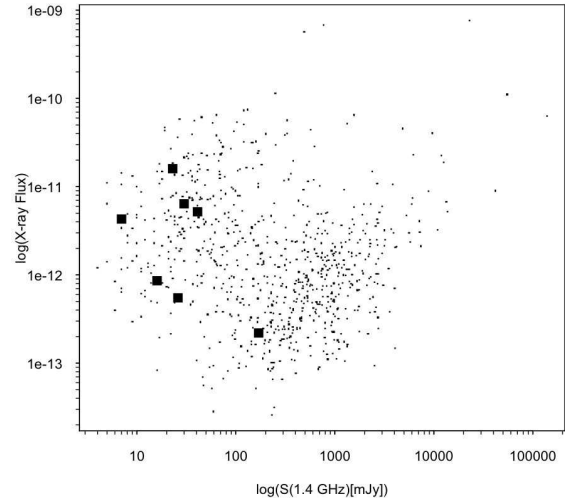
Table 1. Predictions and voting percentages for the Su & Finkbeiner sample, ordered by RA.

Source	P_{AGN}	P_{Pulsar}	Prediction
2FGL J0341.8+3148c	0.786	0.214	AGN
2FGL J0526.6+2248	0.926	0.074	AGN
2FGL J0555.9-4348	0.992	0.008	AGN
2FGL J0600.9+3839	0.952	0.048	AGN
2FGL J1240.6-7151	1.000	0.000	AGN
2FGL J1324.4-5411	0.974	0.026	AGN
2FGL J1335.3-4058	0.864	0.136	AGN
2FGL J1601.1-4220	0.996	0.004	AGN
2FGL J1639.7-5504	0.942	0.058	AGN
2FGL J1716.6-0526c	0.612	0.388	-
2FGL J1721.5-0718c	0.498	0.502	-
2FGL J1730.8+5427	0.986	0.014	AGN
2FGL J1844.3+1548	0.996	0.004	AGN
2FGL J2004.6+7004	0.996	0.004	AGN
2FGL J2115.4+1213	0.996	0.004	AGN
2FGL J2351.6-7558	0.960	0.040	AGN

on a hodgepodge of radio and X-ray observations from various existing catalogues. For radio counterparts, we relied on measurements from the Green Bank (GB6) catalogue at 4.85 GHz (Gregory et al. 1996), the 4.85 GHz Parkes-MIT-NRAO (PMN) survey catalogue (Griffith & Wright 1993), the 1.4 GHz NVSS catalogue (Condon et al. 1998), and the 843 MHz SUMSS catalogue (Mauch et al. 2003). In total, we find that 13 out of the 16 unassociated sources have prominent potential radio counterparts within their *Fermi* 95% confidence error ellipses.

We complement the radio matches with observations from the most ambitious X-ray program for counterpart identification currently underway (Falcone et al. 2011), which aims to image the totality of unassociated *Fermi* sources with the *Swift* X-ray telescope. To date, nine sources have been imaged by *Swift* with times ranging from 1.1 to 19.1 ks of useful exposure. Source extraction to identify all significant X-ray sources within the *Fermi* error ellipses was performed with *wavdetect*. Source positions and positional errors were derived using *xrtcentroid*. X-ray counts (0.1–2.4 keV) were extracted from a circular region with a 20 pixel radius (47"). The background was extracted from an annulus with a 20 pixel (inner radius) to 30 pixel (outer radius) around the source. Throughout, we used *XSELECT* to include counts with grades 0–12. Six out of the nine *Swift* fields have single potential counterparts within their *Fermi* 95% confidence error ellipses.

The ROSAT All-Sky Survey Faint Source Catalogue (Voges et al. 2000) adds four more potential single X-ray counterparts to the final count. Table 2 summarises the counterpart candidates in each case. Of the 16 sources, seven have both radio and X-ray tentative counterparts. Figure 2 shows X-ray flux versus radio flux density of associated *Fermi* AGN. Superposed are the potential seven with simultaneous radio and X-ray counterparts. The results are in line with radio and X-ray counterpart flux levels expected for typical *Fermi* AGN. But we must emphasise that without dedicated spectral classification in the optical these must be considered solid but tentative counterparts at this stage.

**Figure 2.** X-ray flux versus versus 1.4 GHz flux density ($S_{1.4GHz}$). Small dots represent associated *Fermi* AGN. The black squares mark the seven unassociated sources from the Su & Finkbeiner sample with tentative counterparts in both radio and X-rays.

5 INTERPRETATION AND CONCLUSIONS

We have presented class predictions of the Random Forest classifier *Sibyl* for 16 unassociated *Fermi* sources showing line emission at 111 and 129 GeV. We find that 14 out of 16 unassociated sources in the Su & Finkbeiner sample are AGN candidates with prediction accuracy rates greater than 96.5%. In addition, we have detected 10 X-ray and 13 radio potential counterparts distributed over the 16 unassociated *Fermi* 95% confidence error ellipses that would be consistent with the AGN predictions. We emphasise the word potential here as a more exhaustive detective work must be completed to confirm the appropriate counterpart for each unassociated source.

It was postulated that the gamma-ray lines among the unassociated were perhaps connected to dark matter subhaloes dragged into the Galactic disc (Su & Finkbeiner

Table 2. Potential radio and X-ray counterparts for the Su & Finkbeiner sample.

Source	X-ray	Counts s ⁻¹ (0.1–2.4 keV)	Radio	S _ν (mJy)
2FGL J0341.8+3148c			NVSS J034213+314739	S _{1.4GHz} = 23
2FGL J0526.6+2248			NVSS J052643+225337	S _{1.4GHz} = 107
2FGL J0555.9–4348			PMN J0555–4345	S _{4.85GHz} = 61
2FGL J0600.9+3839	Swift J0601.0+3838	$(2.7 \pm 1.0) \times 10^{-3}$	GB6 J0601+3838	S _{4.85GHz} = 322
2FGL J1240.6–7125	Swift J1240.4–7148	$(2.6 \pm 0.1) \times 10^{-1}$	MGPS J124021–714901	S _{843MHz} = 18
2FGL J1324.4–5411	1RXS J132455.7–542020	$(5.4 \pm 2.0) \times 10^{-2}$	PMN J1325–5419	S _{4.85GHz} = 56
2FGL J1335.3–4058			SUMSS J133603–405758	S _{843MHz} = 154
			SUMSS J133544–410113	S _{843MHz} = 21
			SUMSS J133535–405407	S _{843MHz} = 18
2FGL J1601.1–4220			PMN J1600–4227	S _{4.85GHz} = 48
			PMN J1600–4217	S _{4.85GHz} = 46
2FGL J1639.7–5504	1RXS J164023.6–550259	$(2.0 \pm 0.9) \times 10^{-2}$		
2FGL J1716.6–0526c	1RXS J171657.0–053418	$(3.0 \pm 1.2) \times 10^{-2}$		
2FGL J1721.5–0718c	1RXS J172147.4–071923	$(2.3 \pm 0.9) \times 10^{-2}$		
2FGL J1730.8+5427			GB6 J1731+5429	S _{4.85GHz} = 19
2FGL J1844.3+1548	Swift J1844.4+1546	$(7.7 \pm 0.5) \times 10^{-2}$	GB6 J1844+1547	S _{4.85GHz} = 76
2FGL J2004.6+7004	Swift J2005.1+7004	$(7.9 \pm 0.5) \times 10^{-2}$	NVSS J200506+700440	S _{1.4GHz} = 7
2FGL J2115.4+1213	Swift J2115.4+1218	$(1.9 \pm 0.5) \times 10^{-2}$	NVSS J211522+121802	S _{1.4GHz} = 16
2FGL J2351.6–7558	Swift J2351.3–7600	$(1.3 \pm 0.3) \times 10^{-2}$	PMN J2351–7559	S _{4.85GHz} = 47

2012c). However, assuming an isotropic distribution, at least 160 *Fermi* AGN are expected at $|b| \leq 10^\circ$. To date only about 100 are accounted for in the 2FGL (Ackermann et al. 2011). Thus, it makes astrophysical sense that AGN are making up an important fraction of the Su & Finkbeiner sample even at relatively low Galactic latitudes.

In light of these results, the dark matter origin for the narrow gamma-ray features observed by *Fermi* is in question. Were these dark matter sub-haloes (Baltz, Taylor & Wai 2007; Diemand et al. 2008; Kuhlen, Madau & Silk 2009), coincidence between the Galactic Centre and the Su & Finkbeiner sample would certainly confirm a dark matter particle origin (Hooper & Linden 2012). However, the interpretation changes dramatically if the unassociated sources showing an identical line signature are AGN, as implied by both machine-learning classifiers and the multiwavelength arguments just presented. Dark matter could be fed into AGN jets and the Galactic Centre, but such an explanation feels contrived given the hadronic and leptonic dominance in the gamma-ray photon field (Hinton & Hofmann 2009).

Instead, a distinct astrophysical mechanism unrelated to dark matter annihilation and linked to nearby AGN ($z < 0.2$ to avoid redshifted lines) such as accretion, bubble (Su et al. 2010; Profumo & Linden 2012), or jet (Su & Finkbeiner 2012a) phenomenology would appear to be more logical. However, we note that although many *Fermi* AGN display photons above ~ 10 GeV, only a handful of soft AGN ($\Gamma > 2$) exhibit maximum photon energies greater than 100 GeV at $z > 0.5$ (Ackermann et al. 2011). Consequently, Su & Finkbeiner (2012c) might be detecting a fiendish cluster of events imprinted by EBL absorption in the same energy band, but completely unrelated in origin to the emission observed near the Galactic Centre region.

Oddly enough, the lines reported by Su & Finkbeiner (2012c) appear to be only present collectively in unassociated sources and do not appear as pronounced among associated sources, including well-known gamma-ray AGN (Su & Finkbeiner 2012c). Therefore, we must also admit the

possibility that the spectral signatures detected by *Fermi* originate from confounding instrumental or calibration problems (Hooper & Linden 2012). The *Fermi* calibration team will have the final word on the matter very soon, but independent efforts must be made to scan the public *Fermi* archive for gamma-ray lines among individual AGN at $z < 0.2$, as well as in diffuse emission outside the Galactic plane.

We shall hear more about this energy region by the end of the year with the recently unveiled H.E.S.S. II (Becherini et al. 2012; Bergström et al. 2012), and even more sensitive observations will be available later on after completion of the Cherenkov Telescope Array (CTA Consortium 2011). In the future, a dark knight might rise again. Until then, we eagerly await for the final chapter of this intriguing saga.

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